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WEIGHTLESSNESS RESEARCH AT O.N.E.R.A.

H. Le Boiteux

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H. Le Boiteux[1]

ABSTRACT: The state of weightlessness peculiar to satellites and space probes has very important consequences for the crew and for the equipment in the vehicle. After this state is defined, and various possibilities for studying it are presented, details are given regarding its simplest form, free fall. Two facilities built at O.N.E.R.A., one for atmospheric free fall and the other for free fall in a high vacuum, are described and some examples of studies in progress are mentioned.
It is now possible to reduce the gravity effect to 1 x 10^{-9} of its usual value for 3 seconds.

1. Introduction /289*

The state of weightlessness can be defined as corresponding to the apparent absence of weight inside a system which is moving without restraint within a gravitational field.

By reasoning within the framework of Newtonian mechanics, an approximation which is always adequate in practice since modifications of relativity here remain negligible, the force exerted by the moving body on the bodies which it contains is zero relative to the axes linked to the moving system. The same is true for the acceleration if no mechanical, electrical, or magnetic influence from other forces is introduced.

This is true even for the largest satellites built thus far: the Newtonian attraction inherent in their mass remains negligible.

In this case, it is possible to say that the system, with any trajectory, is in "free fall"; this term is also used concurrently with that of "zero gravity". During free fall, the elements composing the system cease to produce the mutual reactions which are usually necessary for balancing their weights. Thus, everything occurs as if the former were rendered null and void (and not the gravitational field.)

For example, let us consider a satellite which describes an

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[1] Scientific Director of General Physics at O.N.E.R.A.

* Numbers in the margin indicate pagination in the foreign text.

orbit around the earth. Its movement is governed by the local value of the gravitational field and by its initial velocity at the moment of launching. It is thus actually in a state of free fall although, because of its tangential velocity, it does not fall to the surface of the Earth. As long as no forces act on it, the objects it contains are in a state of weightlessness.

We should note, however, that this is never achieved absolutely. Actually there are several causes which tend to retard the motion; for example, the atmospheric friction, which, although very weak, remains perceptible if the altitude of the orbit is not sufficient for the specific mass of the gas to be neglected. Another cause is the action of radiation pressure exerted on a satellite which is illuminated by the Sun.

Because of all these causes, there is a residual deceleration whose relationship to the local value of gravitational acceleration is a measure of the relative variation from a state of absolute weightlessness. Thus, for example, it is possible to assume that the effect of the radiation pressure on a satellite weighing 100 kg and presenting a cross-sectional area of one square meter is equivalent to a deceleration which is 10^{-8} times the normal acceleration of the field of gravitation. This figure is significant. It shows the accuracy which must be attained in order to correctly simulate the phenomena with regard to their systematic study.

In the same way, a rocket whose engine has burnt out and which is describing the ballistic part of its trajectory, is in free fall, and achieves the state of weightlessness with greater perfection as its altitude increases. Naturally, for the rocket as well as the /290 satellite, the operation of small propelling devices, intended for modification of the trajectory for example, brings about a supplementary variation relative to total weightlessness, as long as pressure is exerted.

I. Results of the State of Weightlessness

These are numerous and affect a certain number of elements and instruments which are indispensable in the operation of satellites. They also affect the physiological state of the crew, and this is an important aspect of the problem.

Generally, the mechanism is the following: most of the physical laws which govern phenomena observed on the Earth include the idea of the gravitational field. The importance of this fact makes physical factors which are well known but whose order of magnitude is much smaller, unimportant if not negligible. In a state of weightlessness, however, the phenomena cease to be governed by the gravitational field, whose action is almost inexistent, and the factors considered secondary in a conventional statement of the law become preponderant.

One can imagine the great commotion which this fact causes by the very aspect of the phenomena, not only from a quantitative, but also from a qualitative point of view.

The simplest example of this is certainly the one relative to the behavior of liquids in a state of weightlessness, and involving their statics as well as their dynamics. In the gravitational field, the statics of liquids, which are considered as fluids with negligible compressibility, is largely dominated by gravity. On the other hand, the forces of surface tension which regulate equilibrium at the interface (in the case of free surfaces or surfaces in contact with solids) are very weak, and their only effect is a very localized perturbation in the general laws of statics. Nevertheless, a study of them was made; by means of delicate experiments, this study led to a knowledge of the meniscuses linking a liquid with solid surfaces, and to the laws of capillarity.

In a state of weightlessness, the forces of surface tension become preponderant and completely govern the statics. As a result, the forms of equilibrium take on an aspect which is considerably different and somewhat unexpected. In the same way, the laws of movement of fluids are greatly modified.

We will consider these phenomena again later; for the present however, it is evident that when liquids are used on board satellites, entirely new conditions will result which we must account for. For example, the liquid fuels which are used for the operation of auxiliary rockets will have very particular forms of equilibrium in their reservoirs which can even prevent their proper usage.

The circulation of coolants presents even more difficult problems, since, by a similar mechanism, the laws of heat exchange are themselves greatly modified by the state of weightlessness.

We can see that the phenomena thus presented have an effect on the behavior of organic liquids and on the general laws of physiological functions, thus introducing some serious problems. These problems are added to the difficulties of the satellite's crew which result more directly from the apparent absence of weight; this requires veritable re-education.

The modification of the relative orders of magnitude of the various phenomena obliges us to reconsider certain instruments whose operation could be disturbed. In a normal state, due to the gravitational field, there is a fundamental anisotropy in space, with the direction of the gravity constituting an axis which has particular properties. However, in a state of weightlessness, space becomes isotropic again, and more perfectly so as the residual acceleration becomes weaker. This proves the importance of this residual acceleration (or the "degree of weightlessness" achieved), and this notion naturally plays a part in systems which are intended for simulation of the state of zero gravity.

It is convenient to evaluate the residual acceleration as a function of the normal value g_0 = 980.665 cm.sec.$^{-2}$ and to form the equation

$$\gamma = kg_0$$

Let us suppose that we have a liquid occupying a volume V, having a free surface, and let L be the order of magnitude of the linear dimensions of the region of this volume which is occupied by the liquid. The intensity of the capillary forces is of the form σL where σ is the surface tension of the liquid, although the forces of inertia are of the order of $\rho k g_0 L^3$, ρ being the specific mass.

The dimensionless number

$$N = \frac{\sigma}{\rho k g_0 L^2} \text{ (Weber number)}$$

is thus characteristic of the relative importance of the forces.

The laws of equilibrium and movement of fluids are almost uniquely governed by surface tensions, and are thus very different from the normal laws if N becomes much greater than unity. /291

A first result is that the effects of weightlessness become more appreciable as the linear dimensions of the object are reduced. On the other hand, if we observe that the ratio $\sigma/\rho g_0$ for flowing liquids has values of several hundredths ($7.418 \cdot 10^{-2}$ for water, for example), we can see that, for an object whose linear dimensions are of the order of 10 centimeters, the capillarity forces become 100 times the forces of inertia for $k = 7 \cdot 10^{-6}$, i.e. for a residual acceleration which is less than ten millionths that of its weight.

II. Experiments in Weightlessness - Conditions to be Fulfilled

The above discussion indicates the necessity of a complete study of the phenomena which are caused by the state of weightlessness.

From a theoretical point of view, numerous papers have already been published on this question, particularly on the behavior of liquids.

Elliot T. Benedikt [1], beginning with a definition of surface tension and the laws of mechanics included under the heading of energy, has succeeded in establishing a dynamics for liquids in the state of weightlessness which he calls "epihydrodynamics', and which allows for solving problems of equilibrium and (at least in part) problems of transitory movements. He has also dealt with problems of heat transfer.

The development of these theories is being continued. They allow prediction of phenomena to a certain degree of approximation, at least while the geometry of the system is simple. However, it is still necessary to determine the validity of these theories by direct experiments, and also to solve problems whose more complex configurations do not allow us to write out the equations completely.

This necessitates taking measurements in the state of weightlessness. Naturally, we can profit by satellites which are put into orbit for other purposes. But, besides the fact that the procedure is costly and allows for only a limited number of experiments, the operating conditions lack flexibility; certain aspects of the problem, intervening directly in the operation of vital parts of the satellite, must be solved first.

This has very naturally led to research on the processes of simulation which are most accessible and which allow for intensive experimentation.

The conditions to be fulfilled are quite numerous.

First of all, it must be possible to achieve very weak residual decelerations. For certain problems, especially concerning liquids, a value in the vicinity of 10^{-3} to 10^{-5} g_0 will generally be sufficient, at least for a refinement of the studies.

In other cases, we must look much further. We have seen, for example, that if we are concerned with very sensitive accelerometric devices, capable of measuring the retarding forces on the satellites with creditable precision (10 percent), we must attain a sensitivity in the vicinity of 10^{-9} g.

Secondly, we should pay attention to the length of time during which the state of weightlessness is simulated. Here again, these requirements depend greatly on the problem we are treating.

Transition from a normal state to a state of weightlessness is assumed at first to be very rapid. Therefore, the phenomena which we are examing will begin with a transition stage of variable duration.

If our aim is a complete examination of this stage and the final permanent stage, it will obviously be necessary that the simulation time exceed that of the transition stage. This can be a rather long period of time, especially if we wish to achieve equilibrium forms for free surfaces of liquids. The established stage is vibration-damped, and certain authors have thought that the notion of "surface viscosity", initially introduced by Boussinesq in 1913 [2], should be injected here.

Experimentally, it has been found that the transitional stage can last for several seconds.

In other cases (for example, the problem of measuring very weak accelerations), the length of time is less imperative, since the operating principles call for electrical values, and the response time of the instruments is very short.

It is often necessary to consider another point, however. Once the simulation process has started, transition to a state of weightlessness is naturally never instantaneous. It occurs after an intermediate stage whose mechanism and duration vary according to the solutions adopted.

Interpretation of the phenomena whose study we have proposed often requires that this mechanism, which constitutes the initial conditions, be perfectly known and also that the length of time be compatible with the projected experiment. Thus, for example, in studying liquids we are concerned that the transition from a normal state to a state of weightlessness occur in the shortest time possible, i.e., step-wise if plotted on a curve, while in experimenting with a very sensitive accelerometer we should have a more gradual regulation which would allow the instrument to achieve its measurement configuration beginning from a resting position in the field of gravity. /292

The simulation process should also allow for shielding the material from any parasitic disturbance, with very great precision. In fact, no accidental acceleration, in any direction whatsoever, must be allowed to reach the order of magnitude of the amount of deceleration to be measured, and we have seen that the latter can reach $10^{-9}\ g$. This new condition imposes considerable precautions, since many phenomena which are generally neglected (vibrations of buildings, for example) are capable of reaching this value.

Finally, the system should allow for extremely precise measurements and the recording of very different physical values characteristic of the phenomena studied, whose variation in time can be very rapid (as in the case of transitional stages).

III. Various Procedures Employed.

With these conditions in mind, various procedures were deemed possible and used.

Besides systematic measurements on board the satellites, which do not seem to have been very widely employed, the methods which have retained the attention of researchers are the following:

(a) Flight of an aircraft on a ballistic trajectory.
(b) Use of the ballistic stage of flight of an experimental rocket.
(c) Launching into free fall.

The first two methods have the advantage of allowing for a relatively long experimental duration, of the order of one minute in the case of the aircraft and several minutes in the case of the rocket; but this advantage is obtained only at the price of increased expense and a lack of flexibility and reproducibility of the experiments.

That is why launching into free fall, using what some scientists call the "the weightlessness tower", can be considered as the most accessible and the flexible method. It allows for durations which are unfortunately relatively short (of the order of several seconds) but sufficient for a great many studies.

(a) Aircraft in Ballistic Trajectory

This process has been used notably by the Royal Aircraft Establishment in England [3, 4] and by the U.S. Air Force [5].

The ballistic trajectory is carried out approximately along an arc of the parabola with a vertical axis. Durations of the order of 30 seconds to one minute could be expected, but several difficulties limit this value practically to 15 or 20 seconds. In particular, the pilot cannot achieve the necessary trajectory with great accuracy, and the initial conditions in the experiment are not very precise. In order to make up for this, the materials to be studied are placed in a "container" which, when released at the moment of the experiment, floats freely in the aircraft; this ensures a very good simulation of weightlessness. However, the relative displacement of the container relative to the walls limits the duration of the operation in general. In aircraft specially fitted out for these experiments, the pilot, guided by optical instruments or by television, corrects the trajectory in order to keep the container as immobile as possible.

(b) Use of the Ballistic Stage of Flight of a Rocket

A missile is used to release the experimental device in the upper atmosphere at a determined velocity. It remains in free fall until its reentry into the atmosphere, a period during which the experiments are carried out. Thus, by using a Skylark rocket, the R.A.E. could measure heat transfer in liquids in a state of weightlessness [6]. Residual deceleration remains less than $10^{-4}g$ for approximately 4 minutes.

(c) Launching into Free Fall-The Weightlessness Tower

This process consists simply in releasing into free fall from a sufficient height, a capsule which contains the materials which are to be studied. It is certainly the simplest of all, and it allows for easy and inexpensive repetition of a great number of experiments, with great flexibility.

Its drawback is the relatively short duration, generally only a few seconds [7 - 10]. This could theoretically be increased by increasing the height of the fall, but the law of the distance covered shows immediately that this gain is unimportant (the duration increases only as the square root of the height). At the same time, the velocity increases at the end of the fall, and important technological difficulties are involved in recovery of the material. This is why most laboratories now existing, which have adopted this method, are limited to heights which do not exceed 50 meters, corresponding to about 3 seconds of weightlessness. The NASA instrument at Lewis has a height of 170 meters, and allows experiments lasting 5 seconds.

We should note also that an increase in velocity in the course of the fall increases the aerodynamic effect on the capsule (drag), and therefore affects the residual deceleration as well, so that /293
simulation of the state of weightlessness becomes poorer at the end of the fall.

Two remedies can be considered:

(1) The material being studied can be placed in a container inside the capsule. Under these conditions, the relative velocity is very weak and simulation is excellent, but at the price of greater complexity and an appreciable loss in available space.

(2) The free fall can occur in a tube in which there is a high vacuum, thus reducing the drag on the capsule.

Although this solution is more expensive for the initial equipment, it can also be used with a double capsule, and is excellent.

It is the latter which was chosen (after study) at the O.N.E.R.A.

The fundamental problems encountered in building a weightlessness tower are the following:

(a) The time during which the measurements can usefully be taken is related to the height h of the fall by the equation

$$h = \frac{1}{2}gt^2.$$

The aerodynamic braking has very little effect on this duration for practically feasible heights.

It is easy to see that t = 2 sec for h = 20 m, and a little less than 3 sec for 40 m (Fig. 1).

Beyond that, the gain is even less.

The O.N.E.R.A., taking advantage of the fact that its buildings in Châtillon-sous-Bagneux have 13 floors, achieved a height of fall of about 40 m.

(b) Residual deceleration varies during the fall.

The equation for movement is

$$m\frac{\mathrm{d}V}{\mathrm{d}t} = mg - C_x\frac{\rho S V^2}{2}$$

where m is the apparent mass of the capsule, i.e. the mass altered by the aerostatic pressure; C_x is the coefficient of unit drag; S is the cross-sectional area of the capsule; and ρ is the volume mass of the air. We see that the residual deceleration is

$$\gamma_r = g - \frac{\mathrm{d}V}{\mathrm{d}t} = C_x\frac{\rho S V^2}{2m},$$

The degree of simulation is thus

$$\frac{\gamma_r}{g} = C_x\frac{\rho S V^2}{2mg}.$$

The velocity of fall being approximately

$$V = gt$$

we can see that

$$\frac{V_r}{g} = C_x\frac{\rho S g t^2}{2m}.$$

The C_x unit coefficient, for a capsule which is conveniently profiled (a nose cone fitted to a cylindrical section, for example), can be taken as equal to 0.2, the Reynolds number increasing to 550,000, and the regime being laminar.

This gives the variation for $\gamma r/g$ as a function of time (Fig.2).

We can see that γ_r/g becomes 8 to $9 \cdot 10^{-3}$ at the end of the fall for a duration of the order of 3 seconds.

This value is much too high for certain problems, but perfectly convenient for studying liquids, for example.

(c) If a system with a double capsule is put into operation, the equation of movement becomes

$$m_{02}\frac{dV_2}{dt} = m_2 g - C_2\frac{\rho(V_2 - V_1)^2}{2}S_2$$

where the subscripts 1 and 2 refer to the external and internal capsules, respectively, and where

$$m_2 = m_{02} - \rho_2 V_2\left(1 - \frac{\gamma_1}{g}\right)$$

Calculation of $\gamma_r = g - \gamma_2$ allows us again to find γ_r/g as a function of time (Fig. 3).

For a duration of about 3 seconds, we find that $\gamma_r/g = 4\cdot 10^{-6}$, a value which is still too high for studying sensitive accelerometers.

(d) Let us now suppose that the fall took place in a vacuum. /294
The precision of the weightlessness simulation increases as the pressure decreases.

But this calculation becomes more complex. In fact, on the one hand the unit coefficient of drag, C_x, varies greatly with pressure especially when the pressure is below 10^{-3} mbar, where the transition regime, and then the free molecular regime, occur.

On the other hand, below a given pressure, the evacuation is not negligible and produces a fluid current in the tube, which must be accounted for.

Calculations [10] have allowed us to plot the curves in Figure 4.

We see that, for a pressure of 10^{-3} mbar, we can attain a precision of $5\cdot 10^{-7}$ after 3 seconds of fall.

A pressure of 10^{-5} mbar, which is highly feasible by modern methods, permits it to remain constantly below $5\cdot 10^{-8}$

(e) In all these cases, operation in free fall should be carried out without subjecting the capsule to longitudinal or transverse perturbations. This should be done with a precision close to the residual acceleration to be measured, i.e. with considerable accuracy.

In the same way, its axis at that instant should be perfectly vertical, and should not undergo any disturbing oscillation. Some carefully-developed control devices should be provided.

(f) At the end of the fall, for a duration of the order of 3

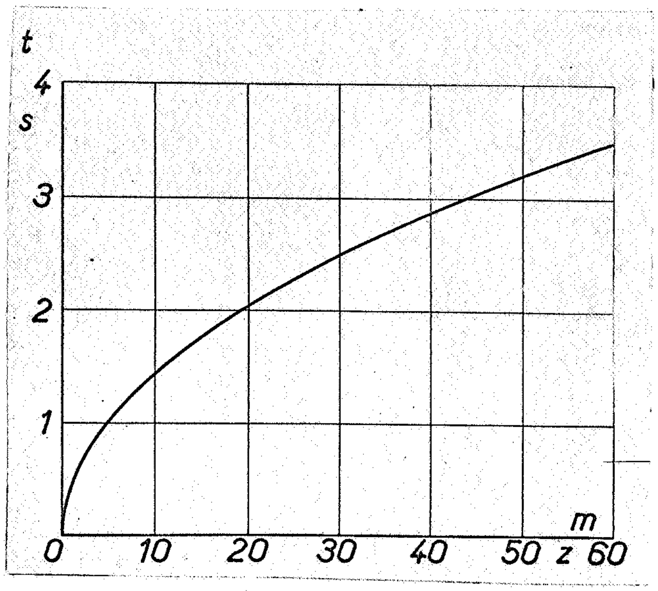

Fig. 1. Time Duration as a Function of the Height of Fall.

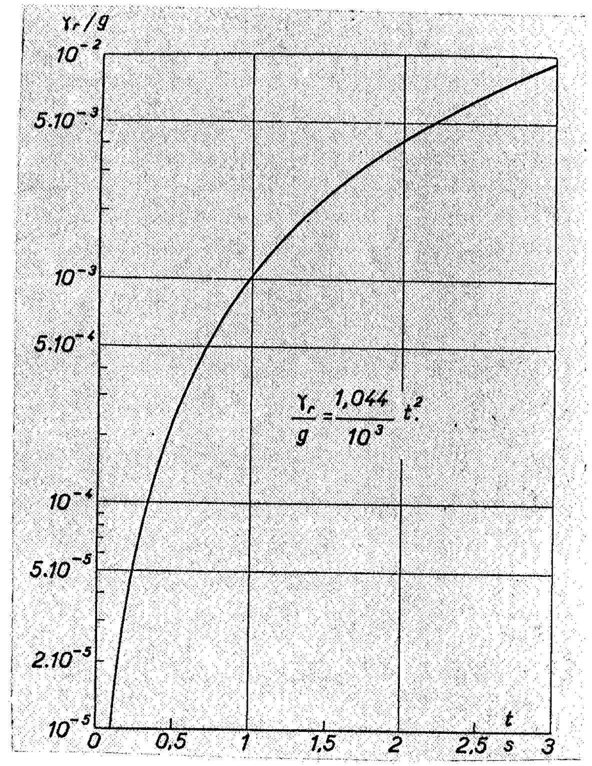

Fig. 2. Degree of Weightlessness as a Function of Time (Free Fall in Air).

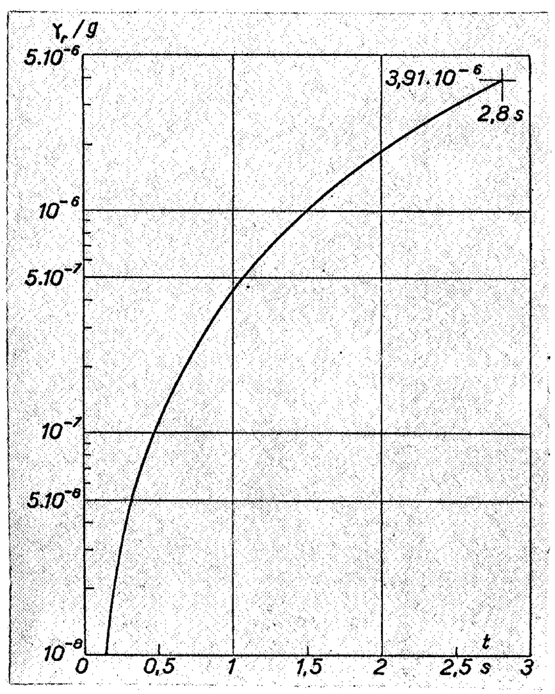

Fig. 3. Degree of Weightlessness as a Function of Time (Use of a Double Capsule in Air).

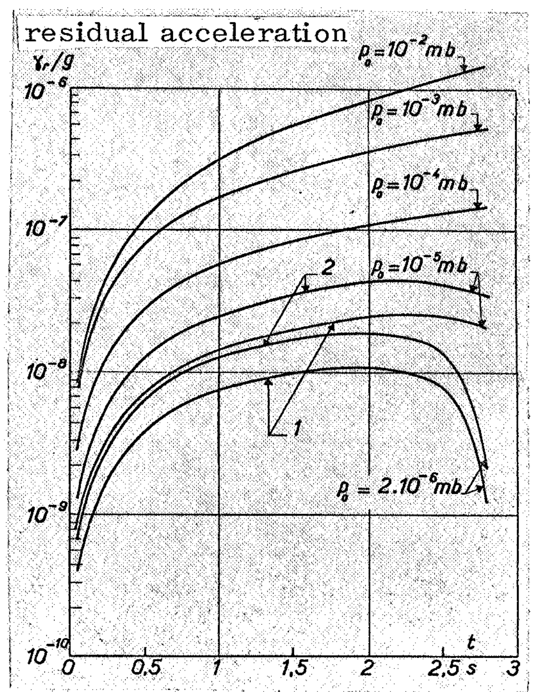

Fig. 4. Degree of Weightlessness as a Function of Time (Free Fall in Vacuum).

seconds the velocity becomes about 30 m per second, or nearly 100 km per hour.

The kinetic energy which this velocity represents, in a capsule whose weight is around 100 kg, should be absorbed at a height which is not too great, because it naturally diminishes the useful height. This should occur without the deceleration exceeding values which are too high and which are detrimental to a good recovery of /295 the material under test.

All these problems, as well as that of re-transmission of parameters measured on board the capsule in free fall, must be solved.

IV. The Two Weightlessness Research Laboratories at O.N.E.R.A.

Tower for Producing Weightlessness in Air

During the initial stage, a laboratory for studying free fall in air was devised for the double purpose of using a simple installation which would suffice for making certain studies and serving as a test-stand for calculation and operation of essential elements which are necessary in building a weightlessness tower using a vacuum.

The system using air was mounted in the shaft of an unused freight elevator, which allows for a height of fall of around 40 m. Its dimensions permit use of an experimental capsule, 0.30 m in diameter in the cylindrical section and 1 m long, weighing 80 kg. The devices to be tested are placed in holders with standard dimensions and introduced into the capsule just before release; this allows simultaneous preparation for diverse experiments in the laboratories. Figure 5 shows the capsule containing the experimental materials, and Figure 6 shows one of the holders equipped for experiments with the sensitive accelerometer.

Two release systems were used.

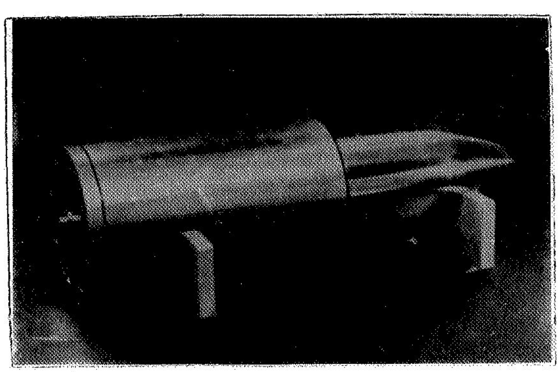

Fig. 5. Capsule for Weightlessness Experiments.

The simpler one consists in using an oxy-acyetylene torch to cut a cable from which the capsule is suspended before the experiment. The experiment showed that with a steel cable, the duration of the operation to produce weightlessness is not very greatly reduced (around 100 m sec) because of the creep of the metal before it is cut through. On the other hand, the use of a nylon cable allows us to obtain a liberation time of approximately 1 m sec, which produces a result that is very close to standard.

The command for release which causes the pivoting of the torch can be given only after checking the side-to-side motion of the capsule. This check is produced by two light beams arranged in a *V*, tangent to the walls and detected by photoelectric cells. The sensitivity of this device is very great, and ensures that at the moment of release the slope of the axis to the vertical does not exceed one minute of angle.

Figure 7 shows the capsule ready to be released.

A second method had to be studied particularly for the fall in vacuum, for which it is naturally impossible to use the simple method of the torch.

It called for a suspension of "bistable magnetic" type, i.e. for a device in which transmission of an impulse interrupts the magnetic flux, thus suppressing the sustaining force in a short

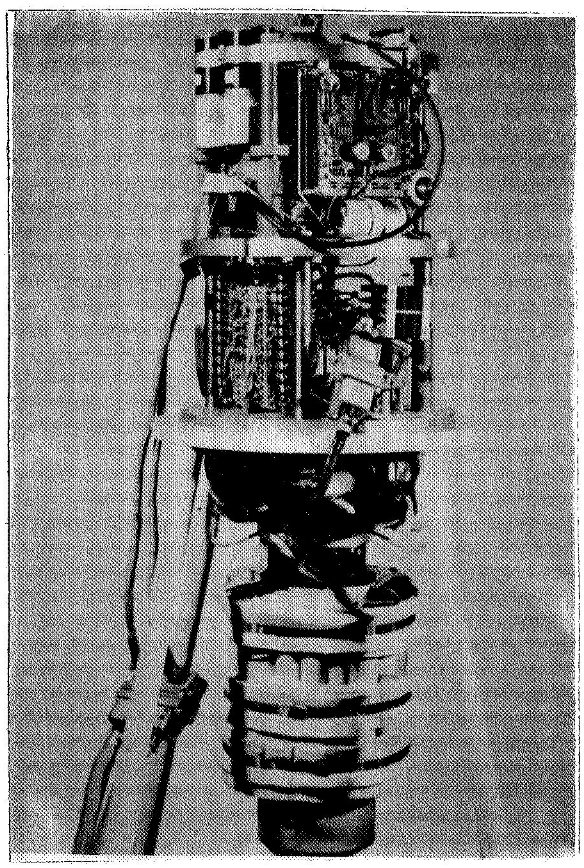

Fig. 6. Measuring Holder for Experiments with a Sensitive Accelerometer.

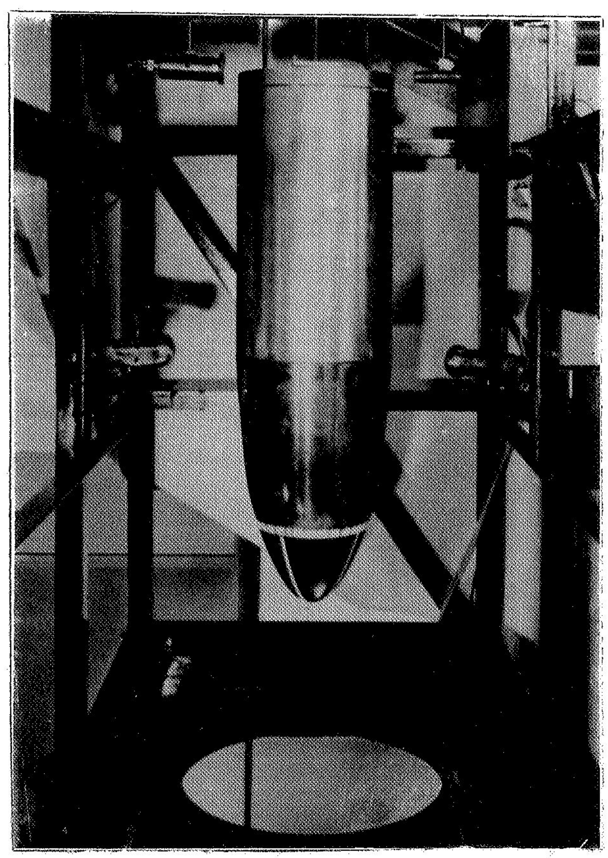

Fig. 7. Capsule Ready for Release.

time (around 100 m sec).

Particular precautions had to be taken in order that except for that suppression, no important transverse impulse would be communicated to the capsule. These precautions consist of precise regulation of input voltages and contact surfaces. This regulation is carried out once and controlled by an interferometric device using coherent light, for a fall which is limited to around 10 centimeters. /296

Thus, it was possible to limit the angular velocities at the moment of release to 1/10 degree/sec.

Recovery of the material at the end of the fall is an important problem. It was solved at O.N.E.R.A. by a method which can be directly transposed to the case of a vacuum.

The capsule's kinetic energy is absorbed by deformation beyond the elastic limit in two metallic systems. The first is a stainless-steel collar which has an opening whose diameter is less than that of the cylindrical section of the capsule, and is therefore distorted by it. The second has 8 powerful springs which support the collar and are attached to the framework of the recovery device. These springs, with contiguous turns, are 0.5 meters long at the start and about 4m long after recovery. The whole system was calculated so that at no time would the deceleration exceed 16g (Fig.8).

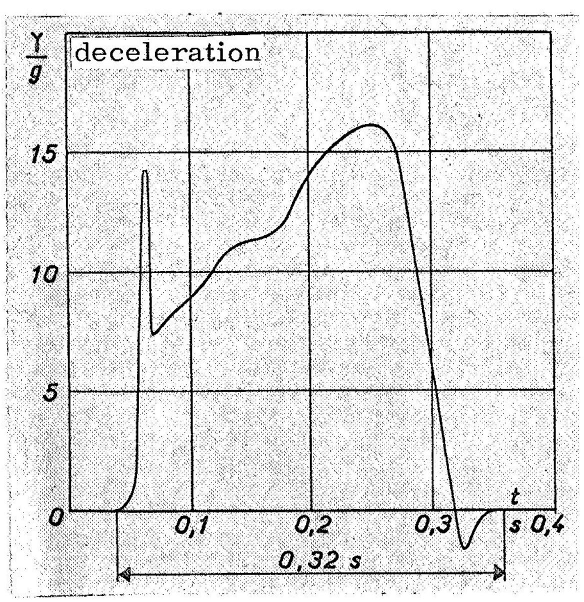

Fig. 8. Deceleration of the Capsule in the Course of Recovery.

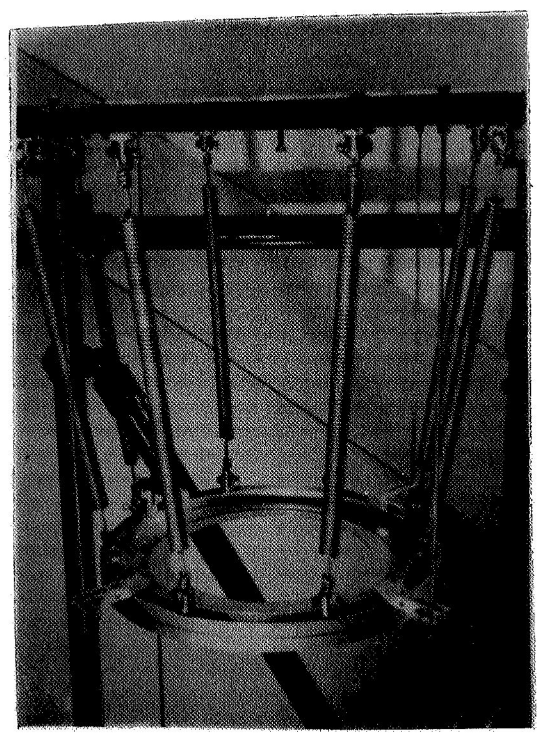

Fig. 9. Recovery Device

The recovery system is centered very precisely at the upper point of attachment, taking into account the Coriolis effect due to the motion of the Earth, which here is about 4 mm.

Operation of the system is found to be perfectly satisfactory and ensures a very high level of security.

Tower for Producing Weightlessness in Vacuum.

Standing 13 stories high in an elevator shaft, it is 47.50 m long and allows for a free fall of 39.90 m.

The tube, made by ALCATEL from sections welded in place, is made of a light alloy (AG 3); the condition of the interior surface was given particular attention in order to allow for a vacuum of 10^{-5} mb when evacuated. /297

In the first stage, however, it is limited to 10^{-3} mbar.

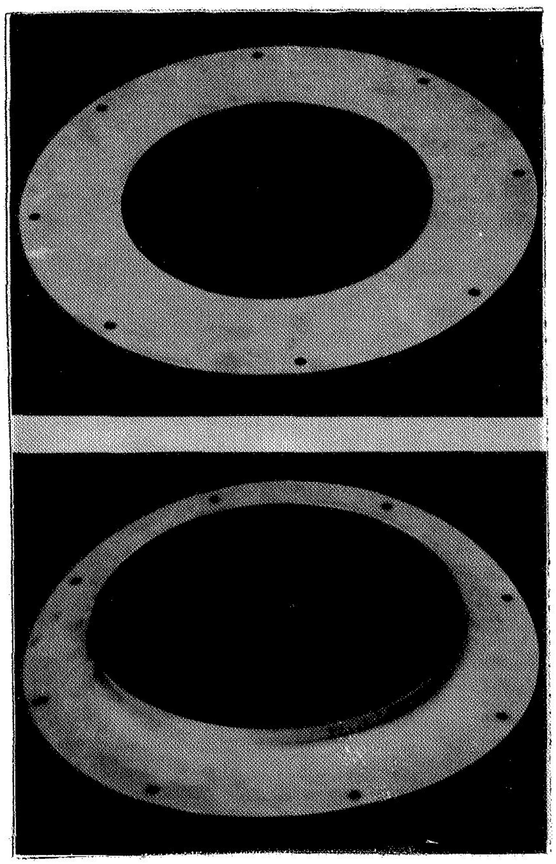

Fig. 10. Collar Before and After Distortion.

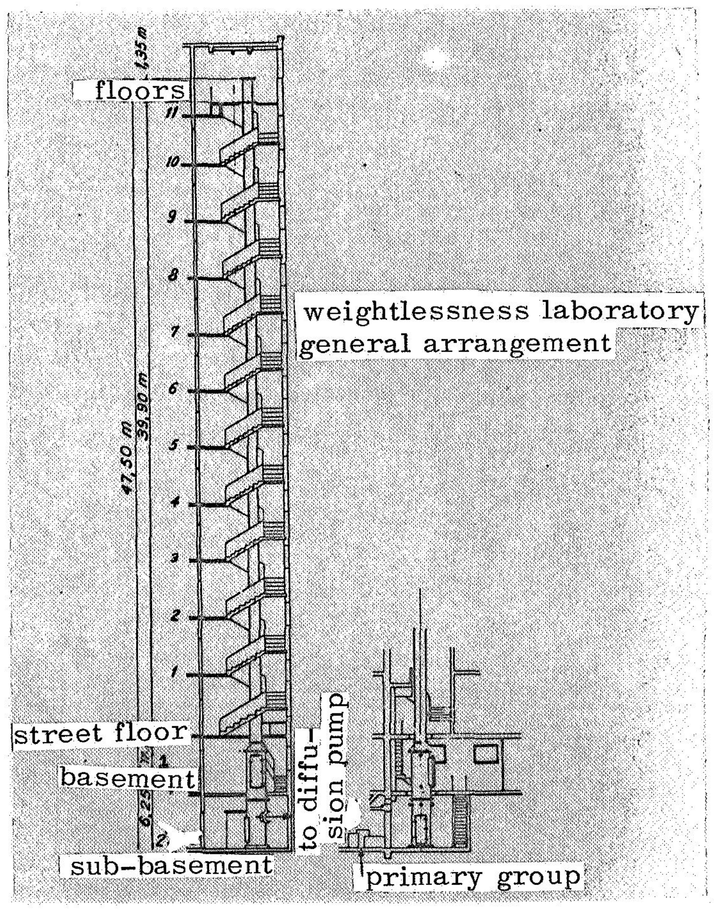

Fig. 11. Diagram of the Weightlessness Tower for Studying Free Fall in Vacuum.

The tube has a diameter of 0.75 m; it rests entirely on its base, and is only supported laterally. Its lower part is made of steel, coated with a 30-micron-layer of nickel, and has a diameter increased to 1.20 m. This lower part is intended for receiving the recovery device, which is identical to the one already described, made of stainless steel. In the first stage, a group of 3 pumps (two centrifugal pumps and one Roots pump) ensure maintenance of a pressure of $5 \cdot 10^{-4}$ mbar (for the 10^{-3} predicted in the calculation). Later we will have to add a diffusion pump to this system to obtain more than 10^{-5} mbar.

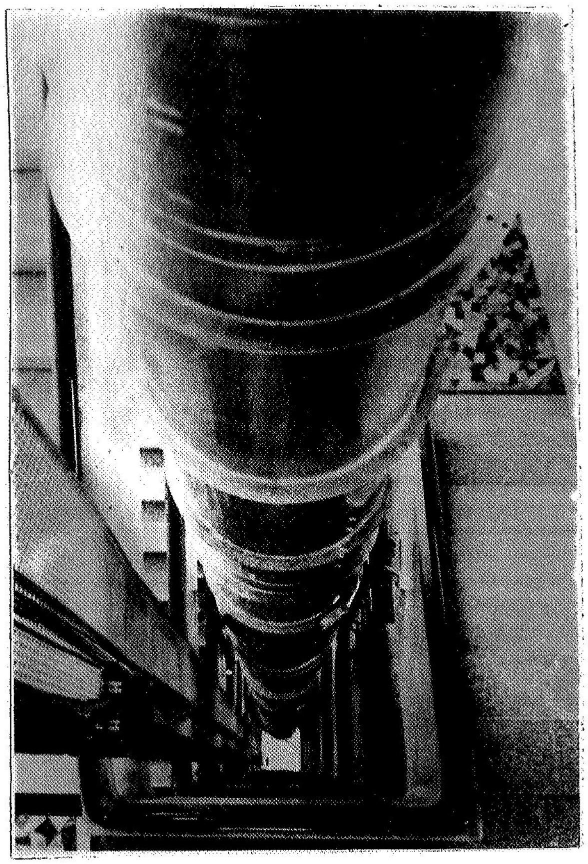

Fig. 12. Weightlessness Tube for Studying Free Fall in Vacuum.

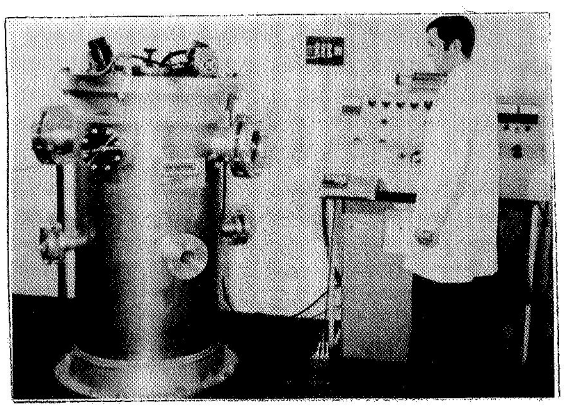

Fig. 13. Upper Part of the Weightlessness Tube, and Control Panel for the Release Mechanism.

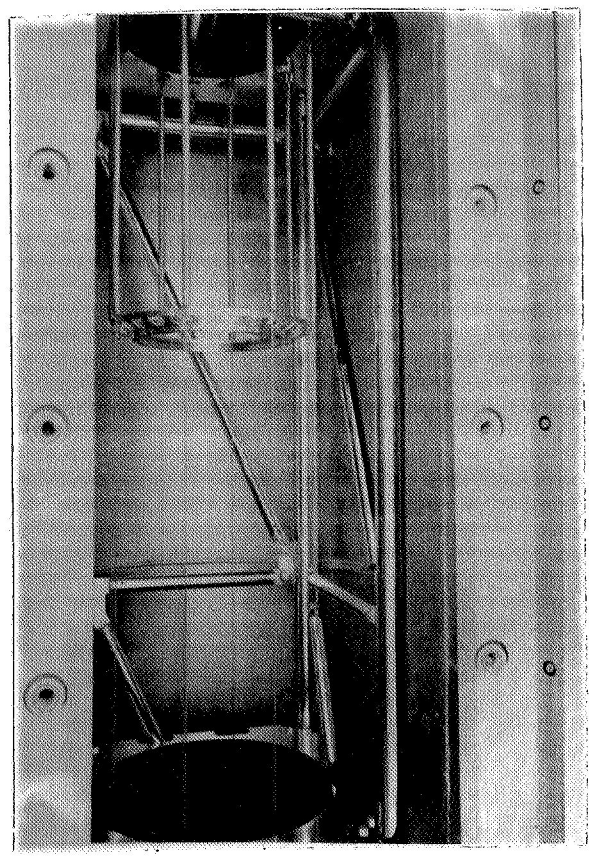

Fig. 14. Recovery Device at the Base of the Weightlessness Tube (Before the Experiment)

Figure 11 is the diagram of this installation, and Figures 12, 13, 14 and 15 are photographs of its essential parts.

This installation, which was put into operation in February, 1966, is functioning continuously; its special task is the design and calibration of a high-sensitivity accelerometer, although the tower for studying free-fall in air, which started operating in 1965, is now specializing in studies related to the behavior of liquids.

A very important point to be considered in conducting these studies is the transmission and recording of the measurements taken on board the capsule.

Up to this time, two methods have been used by O.N.E.R.A.

The first is the high-speed photography (several hundred frames per second) of phenomena to be studied, using a camera mounted on board; it allows not only a qualitative examination but also a quantitative analysis, which is particularly useful in studying the behavior of liquids.

The second, more general in its applications, consists in transmitting the measurements by radiotelemetry. For this purpose, O.N.E.R.A. used a transmitter with 5 continuous channels, which had previously been used there for other studies and whose general characteristics are well suited for this purpose. The frequency used is 101 MHz.

However, a delicate problem was that of the receiving antenna /298 in the case of the vacuum tube. Because the latter formed a completely sealed metallic enclosure, we have to put the antenna inside and to find a device which would ensure good reception during the fall despite the rapid movement of the transmitter. We found a very satisfying solution in the form of horns mounted at the two extremities of the tube and a wire which was stretched along the whole length of the tube and consisted of a coaxial cable without an exterior conductor [11].

Figure 16 shows the group of control panels monitoring the vacuum, telemetric reception, and recording. This apparatus is located in the upper part of the installation. Since the time for reaching the vacuum limit does not exceed two hours, and since the various procedures are greatly facilitated by hoisting devices associated with the tube, we can very easily carry out at least two experiments a day. If we add the even greater possibilities for a device for studying free fall in air, we see that O.N.E.R.A. is particularly well situated for conducting numerous studies of weightlessness phenomena on a very wide range of degrees of simulation and under conditions of perfect reproducibility.

V. The Experiments at the Weightlessness Laboratory

As we have already indicated, these studies essentially involve two domains: on one hand, all questions concerning the behavior of liquids, and, on the other hand, the study of the measurement of very weak accelerations and the operation of /299
corresponding instruments.

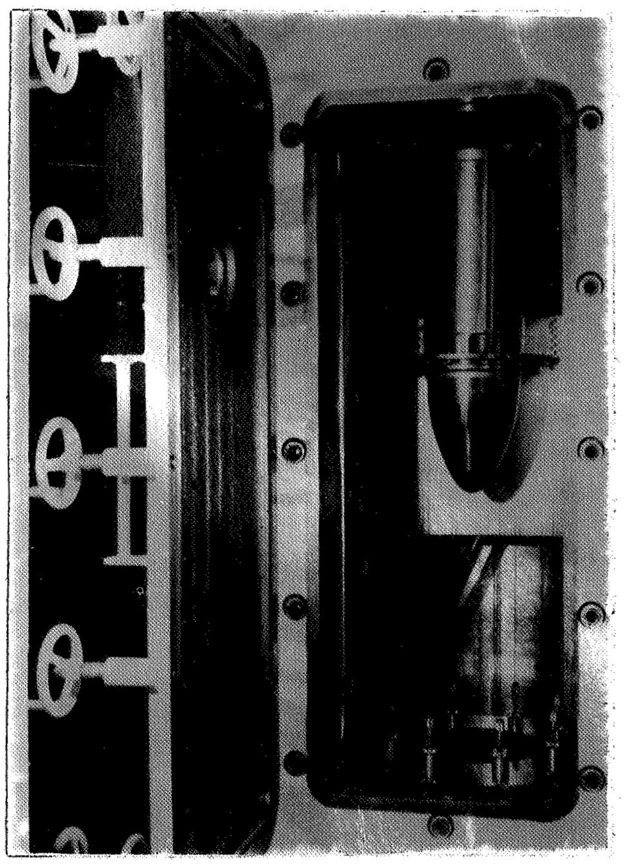

Fig. 15. Recovery of the Capsule in the Vacuum Tube

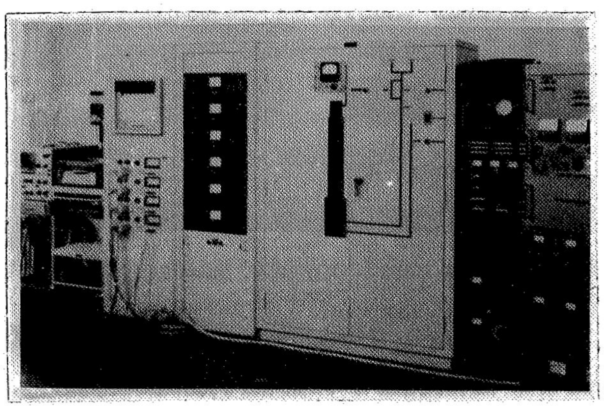

Fig. 16. Instruments for Control, Reception, and Recording.

Liquids in a State of Weightlessness.

All the effects mentioned, whether they are static or dynamic, result from the predominance of surface tension forces in this state.

Naturally, this results in the equilibrium form of free surfaces being generally very different from the form found in the normal state.

Benedikt's theory [1] is based on a consideration of the minimum energy which characterizes equilibrium and on the constancy of the liquid-solid angle of coincidence, or the "angle of contact". As a result, the phenomena immediately take on very different aspects according to the nature of the fluid considered, and, especially, according to its "wetting" or "non-wetting" characteristics relative to the solid which constitutes the wall; these notions are exactly those defined earlier in studying surface tension.

A first result is that, for non-wetting liquids, supposedly contained in a spherical vessel in order to simplify the calculations, the final equilibrium should correspond to the formation of a liquid sphere, without contact with the walls.

The experiment clearly confirms these predictions.

For the fall times which were achieved, on the order of 3 sec., final equilibrium is not reached; however, the examination of successive forms when the test capsule is dropped repeatedly allows measurement of their characteristic frequencies, the damping factor, and the response time - all the essential values for prediction of phenomena and comparison with theory.

Figures 17 and 18 show the results obtained under these conditions with pure water on the one hand and mercury on the other [12].

Figure 19 shows the measuring holder equipped for these studies.

The studies also involved the influence of the numerous parameters involved: the form and dimensions of the receptacles, rate of filling, and pressure in the gaseous phase; mixtures of miscible or immiscible liquids; modification of surface tension by addition of a substance to a solution, etc.

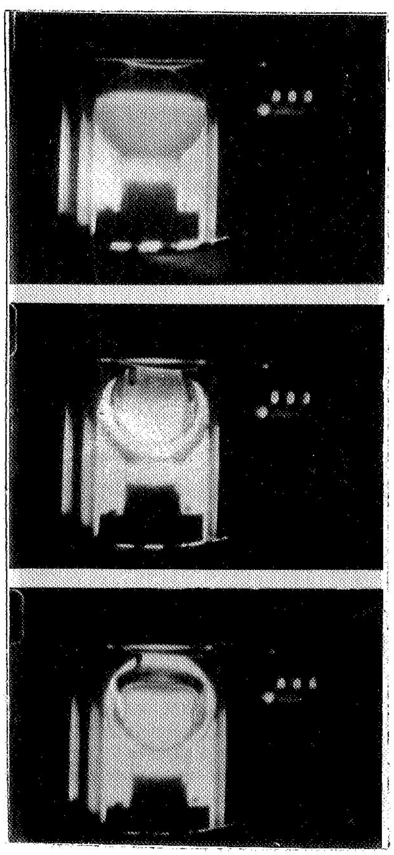

Fig. 17. Transition State for a Wetting Liquid (Water).

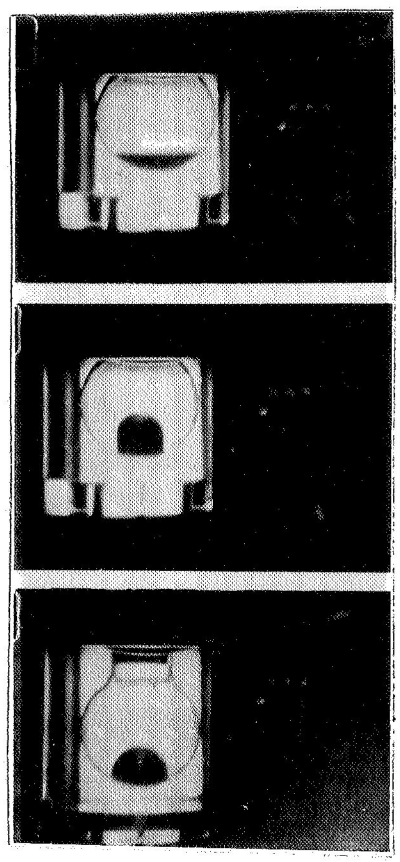

Fig. 18. Transition State for a Non-Wetting Liquid (Mercury).

A second important point concerns the thermodynamic effects in liquids in a state of weightlessness, especially the influence on changes of state (boiling for example). Since the boiling point of a liquid depends on the hydrostatic pressure, we should expect that it would be very homogeneous in the whole volume in a state of weightlessness.

In the same way, the latent heat of evaporation is influenced by the process of formation of bubbles, which depends on the field of gravity. Various authors have noted that the state of weightlessness considerably modifies conditions in the case of "film" boiling, and it modifies conditions much less in the case of "nu- /300
cleate" boiling (formation of bubbles on impurity nuclei).

Other studies are concerned with convection phenomena which are necessarily modified by the state of weightlessness. We know that the customary theory involves the Grashof number which contains the acceleration due to gravity.

All this research sometimes necessitates the development of delicate methods of measurement. This is being done at O.N.E.R.A.,

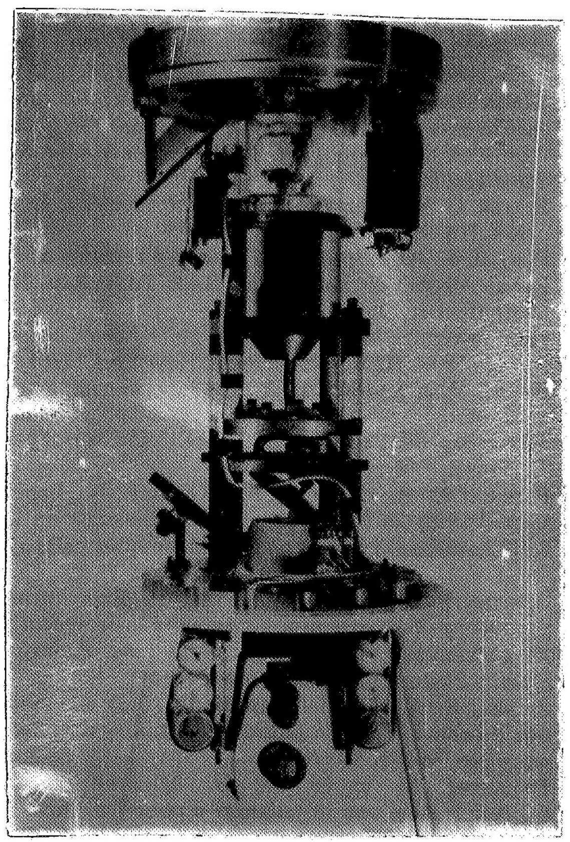

Fig. 19. Measuring Holder Equipped for Studying Liquids in a State of Weightlessness.

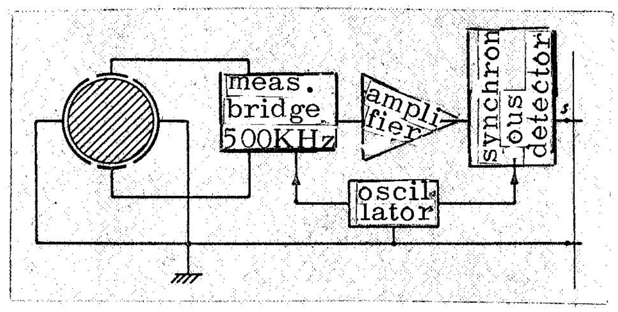

Fig. 20. Diagram of the Detection Circuit (For One Direction)

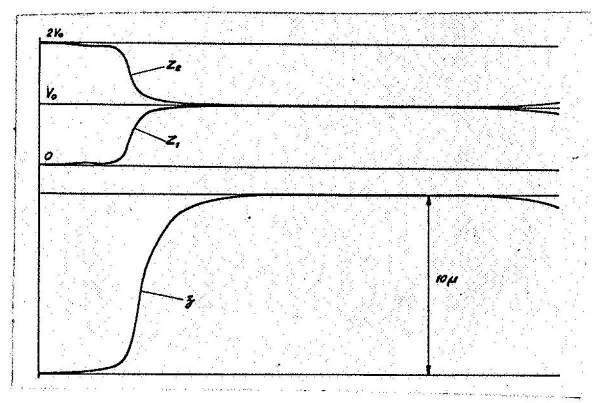

Fig. 21. Record of Measurements by a High Sensitivity Accelerometer.

together with a continuation of the corresponding theoretical studies.

An important point concerns the behavior of cryogenic liquids whose use on board satellites is increasingly under consideration (liquid nitrogen, hydrogen, and helium). Special cryostatic devices were developed at O.N.E.R.A. for these studies which are now in progress.

We are also working on methods of controlling the motion of liquids in a state of weightlessness. One of these methods could be the use of electrophoretic phenomena which involve forces much greater than surface tensions.

Measurement of Very Weak Accelerations /301

The interest in these measurements and the orders of magnitude to be expected have already been examined at the beginning of this article.

In order to attain sensitivities of the order of 10^{-9} g, the processes usually used are no longer applicable. Practically speaking [15], it is already becoming difficult to make conventional accelerometers for use at values of 10^{-4} to 10^{-5} g.

Moreover, the problem becomes very complex, since the accelerometer must be capable of withstanding increased accelerations (of the order of several g's at the moment of launching the satellite, for example), as is the general case.

Finally, precise calibration of such instrumnets poses some delicate problems which can be solved only in a state of weightlessness.

O.N.E.R.A. has undertaken the study of an accelerometer which is capable of measuring accelerations of the order of 10^{-9} g, with a wide measurement range (from 10^{-3} to 10^{-9} g), and capable of being launched and withstanding the corresponding very severe environmental conditions.

The instrument must measure acceleration in three trirectangular directions simultaneously, without interaction among the three lines.

The principle used is that of a sphere held by electrostatic fields [16] inside an equally spherical cavity, the air gap being extremely reduced. Electrodes for detection of position are connected to the operating electrodes intended for the operating mechanism. This detection is accomplished by measuring the variation of capacity due to motions of the sphere under the influence of the acceleration to be measured. The spherical shape is attained with very great accuracy by using surface-polishing methods which are routine in optics. The sphere is monitored by means of capacity detection. It ensures a good reduction of interactions among the three measuring directions, since if the sphere were absolutely perfect, the detecting electrodes would not sense the rotation, and the holding mechanism would not be modified. The sensitivity of the capacitance detector used allows detecting displacements of the sphere by 10^{-10} m.

The diagram of the detection circuits if given in Figure 20. Figure 6 shows an accelerometer with three axes.

The first tests were made on a uniaxial instrument. Its characteristics were the following:

Threshold Sensitivity 10^{-6} g
Measurement Range 10^{-3} to 10^{-6} g
Characteristic Frequency 7 H_z

In order to regulate the absorption coefficient for the accelerometer, the spherical chamber containing the sphere is placed under vacuum in order to avoid viscous friction, and damping is accomplished by an electronic correcting circuit.

The experiment was carried out in the weightlessness tube by regulating the residual pressure in it so as to cover the useful range. The telemetric system allowed simultaneous recording of the reading of the accelerometer and of the supply voltages of both the upper and lower electrodes of the control system (Fig. 21).

Conclusion

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Because of the importance of the effects of weightlessness in space research, we must have methods of simulating this condition for systematic study in a laboratory.

The simplest method consists in launching the materials to be studied into free fall. Although this method is limited with respect to time, it allows a large number of problems to be handled with satisfactory accuracy.

The National Office of Aerospace Studies and Research (O.N.E.R.A.) is therefore equipped with two devices employing this principle, which also allow various other studies.

In order to achieve the maximum possible simulation of absolute weightlessness, one of these installations provides for free fall in a high vacuum.

Under these conditions, a residual deceleration of 10^{-7} to 10^{-9} g is possible, and this value is sufficient for the most delicate studies now envisaged, since it corresponds to the values found in the case of satellites: These values can be attributed to the final causes for retardation of satellites outside the atmosphere.

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